

# EVIDENCE FOR A GAS-RICH MAJOR MERGER IN A PROTO-CLUSTER AT $Z=2.5$

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## ABSTRACT

Gas-rich major mergers in high-redshift proto-clusters are important events, perhaps leading to the creation of the slowly rotating remnants seen in the cores of clusters in the present day. Here, we present a deep Jansky Very Large Array observation of CO  $J = 1-0$  emission line in a proto-cluster at  $z = 2.5$ , USS1558-003. The target field is an extremely dense region, where 20 H $\alpha$  emitters (HAEs) are clustering. We have successfully detected the CO emission line from three HAEs and discovered a close pair of red and blue CO-emitting HAEs. Given their close proximity ( $\sim 30$  kpc), small velocity offset ( $\sim 300$  km s<sup>-1</sup>), and similar stellar masses, they could be in the early phase of a gas-rich major merger. For the red HAE, we derive a total infrared luminosity of  $L_{\text{IR}} = 5.1 \times 10^{12} L_{\odot}$  using MIPS 24  $\mu\text{m}$  and radio continuum images. The  $L_{\text{IR}}/L_{\text{CO}}$  ratio is significantly enhanced compared to local spirals and high-redshift disks with a similar CO luminosity, which is indicative of a starburst mode. We find the gas depletion timescale is shorter than that of normal star-forming galaxies regardless of adopted CO-H<sub>2</sub> conversion factors. The identification of such a rare event suggests that gas-rich major mergers frequently take place in proto-clusters at  $z > 2$  and may involve the formation processes of slow rotators seen in local massive clusters.

*Subject headings:* galaxies: evolution — galaxies: high-redshift — galaxies: ISM

## 1. INTRODUCTION

Properties of galaxies seen in the local universe strongly depend on their surrounding environments, as is well known from the morphology–density relation. Early-type galaxies are frequently observed in high-density regions such as clusters and late-type galaxies are common in low-density regions (Dressler et al. 1997). The ATLAS<sup>3D</sup> survey further demonstrates that early-type galaxies are divided into two kinds of populations based on the kinematics: fast rotators and slow rotators (Emsellem et al. 2011). This categorization makes the trend in the morphology–density relation more prominent. Whereas fast rotators, which form the majority of early-type galaxies, appear in a wide range of environments, slow rotators reside exclusively in dense cores of mature clusters (Cappellari et al. 2011).

Such spatial segregation and the difference in their kinematics could be related to formation processes and subsequent quenching mechanisms of star formation, which probably take place at high redshift. In theoretical models, gas-rich major mergers leading to a spin-down of remnants successfully produce simulated slow rotators and are considered to be one of the possible formation processes of slow rotators (Naab et al. 2013). Given high number densities of star-forming galaxies in proto-clusters at  $z > 2$  (e.g. Tanaka et al. 2011), we naturally expect a high frequency of major-merger events. What is important here is whether they are interactions between gas-dominated systems. While stellar components within galaxies are collisionless, systems comprising gas

are dissipational. Therefore, gas-rich major mergers trigger an intense, dusty star formation due to shocks and an inflow of gas that has lost its angular momentum, as well as establishment of the outer profile through violent relaxation (Mihos & Hernquist 1996).

CO observations are critical for measuring the molecular gas mass within galaxies,  $M_{\text{gas}}$ , and investigating the star-formation mode characterized by the star-formation efficiency,  $\text{SFE} = \text{SFR}/M_{\text{gas}}$ , and the gas depletion timescale,  $\tau_{\text{depl}} = M_{\text{gas}}/\text{SFR}$ . CO studies at high-redshift have rapidly developed over the past years not only for very bright galaxies in the dust emission such as submillimeter galaxies (SMGs; Frayer et al. 1998; Neri et al. 2003; Greve et al. 2005; Tacconi et al. 2008; Engel et al. 2010) but for optical/near-infrared selected galaxies such as  $BzK$  galaxies (e.g. Daddi et al. 2010; Tacconi et al. 2013). However, most of them observe high-excitation CO lines mainly using the Plateau de Bure Interferometer. This significantly affects the estimates of molecular gas mass because high- $J$  lines trace dense gas regions rather than total gas reservoirs probed by CO  $J = 1-0$  emission.

In a cluster field at  $z = 0.4$ , Geach et al. (2011) detect the CO  $J = 1-0$  line from five dusty star-forming galaxies and find the environmental dependence of SFE is not seen. Aravena et al. (2012) also find that the SFEs of two galaxies in a proto-cluster at  $z = 1.5$  are comparable to that of field galaxies at similar redshift. On the other hand, Ivison et al. (2013) discover four CO luminous galaxies across an  $\sim 100$  kpc region at  $z = 2.4$  and find that two of them have a high SFE. No conclusive

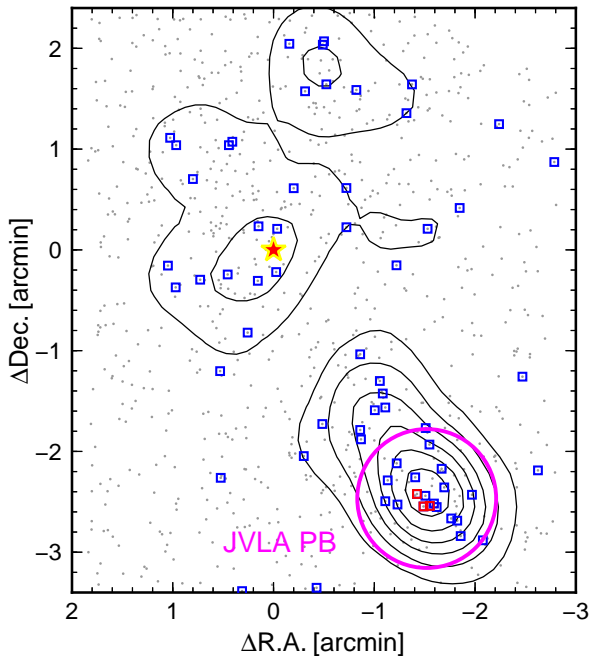


FIG. 1.— A 2-D map of the USS1558 proto-cluster at  $z = 2.5$ . Red and blue squares represent CO-detected and non-detected H $\alpha$  emitters (HAEs), respectively. Coordinates are relative to the radio galaxy (a red star). The primary beam is shown by a magenta circle. Contours denote the local number densities ( $\Sigma_{5th}$ ) of all HAEs, in a step of  $2 \text{ Mpc}^{-2}$ .

result could be obtained due to a small sample size. In this paper, we report results from a deep CO  $J = 1 - 0$  observation of a proto-cluster at  $z = 2.5$  to search for gas-rich galaxies and see if there is any environmental effect of the star-formation mode in the formation phase of the progenitors of cluster early-type galaxies seen today. We assume the Salpeter initial mass function (Salpeter 1955) and cosmological parameters of  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$ , and  $\Omega_\Lambda = 0.7$ .

## 2. OBSERVATION

### 2.1. USS1558-003 proto-cluster at $z = 2.5$

Our target is a proto-cluster at  $z = 2.5$ , USS1558-003, where an over-density of massive, red-sequence galaxies has been discovered around a radio galaxy (Kodama et al. 2007). This region has also been observed as part of a systematic H $\alpha$  narrow-band imaging campaign with MOIRCS on Subaru Telescope called “MAHALO – Subaru” project (Mapping H $\alpha$  and Lines of Oxygen with Subaru; Kodama et al. 2013), and it is found to host numerous H $\alpha$  emitters (HAEs; Hayashi et al. 2012). Membership of about half of the 68 HAEs has been spectroscopically confirmed with a success rate of 70% (Shimakawa et al. 2014). An extremely dense clump lies about three arc-minutes away from a radio galaxy in the southwest (Figure 1). Because the dynamical mass of this clump is estimated to be  $\sim 10^{14} M_\odot$  from the H $\alpha$  spectroscopy, it is expected to evolve into a single massive system with  $> 10^{15} M_\odot$  similar to the Coma cluster (Shimakawa et al. 2014). Therefore, this proto-cluster is very likely the site where slow rotators, which will eventually dominate a rich cluster by the present-day, are just in their formation phase.

### 2.2. JVLA observations

We have conducted CO  $J = 1 - 0$  emission line observations with the Jansky Very Large Array (JVLA) during February–April 2013. The target field includes 20 HAEs at  $z = 2.5$  (Figure 1), of which 12 have spectroscopic redshifts based on their H $\alpha$  line. The observations were made in the compact D array configuration to securely detect emission lines from entire galaxies. Because the narrow-band survey samples star-forming galaxies at  $z = 2.53 \pm 0.02$ , the CO  $J = 1 - 0$  emission line ( $\nu_{\text{rest}} = 115.271 \text{ GHz}$ ) can be observed with the Ka-band receiver ( $\nu_{\text{obs}} = 33 \text{ GHz}$ ), providing the primary beam size of  $82''$ . The WIDAR correlator was set up to cover 32.078–34.082 GHz, corresponding to the CO line at  $z = 2.382\text{--}2.593$ . We observed the standard calibrators 3C286 (1.9 Jy) for bandpass and flux calibration. Phase calibration is performed with observations of J1557-0001 (0.7 Jy). The data are processed through the VLA CASA Calibration Pipeline (McMullin et al. 2007). Channels at the edges of each spectral window are flagged, which brings 14 spectral gaps of 14 MHz. The total integration time is 14 hours on source. Two kinds of CO maps are reconstructed with the CASA task CLEAN, using “briggs” weighting with a robustness parameter of -0.5 and natural weighting with 5.0, which provide a synthesized beam of  $2.2 \times 1.9 \text{ arcsec}^2 / 3.0 \times 2.5 \text{ arcsec}^2$  and a rms level of  $80\text{--}90 \mu\text{Jy beam}^{-1} / 40\text{--}50 \mu\text{Jy beam}^{-1}$  per 2 MHz channel ( $18 \text{ km s}^{-1}$ ) before the primary beam correction, respectively.

### 2.3. Spitzer MIPS $24 \mu\text{m}$ data

We use a *Spitzer*/MIPS  $24 \mu\text{m}$  image to identify dusty star formation and estimate total infrared (IR) luminosities of HAEs. The data is retrieved from the *Spitzer* Heritage Archive. Data reduction is performed in a standard manner (flat fielding, background subtraction and mosaic) using MOPEX software (Makovoz & Khan 2005). Source extraction and PSF-fitted photometry are performed using APEX module in MOPEX. The limiting flux reaches to  $5\sigma \sim 150 \mu\text{Jy}$  in the final combined image.

## 3. RESULT

### 3.1. Detections of CO $J=1-0$ emission line

We search for the CO  $J = 1 - 0$  emission line within a  $0.5 \text{ arcsec}$  radius from the position of 20 HAEs by using the 10 MHz ( $\sim 92 \text{ km s}^{-1}$ ) binned data cube. To avoid spurious detections, we identify a  $> 3\sigma$  peak associated with two additional bins of  $> 1.5\sigma$  significance. The probability that such signals are detected, by chance, in the frequency range (32.471–32.841 GHz, 37 bins) of the narrow-band redshift is estimated to be 0.5% in Gaussian noise. Actually, negative peaks are not seen except for one object located at the edge of the primary beam. The significance of the detection is defined by the signal-noise ratio of peak flux in the 10MHz binned cube. ID 191, ID 193, and ID213 are eventually detected in 6.9, 6.3, and  $3.8\sigma$ , respectively. The separation between ID 191 and ID 193 is about  $4 \text{ arcsec}$  corresponding to  $32 \text{ kpc}$  in the physical scale and the velocity offset is  $300 \text{ km s}^{-1}$  (Figure 2). We also look into the relation between the detection rate of CO emission and the rest-frame optical color. Our sample consists of four red HAEs with

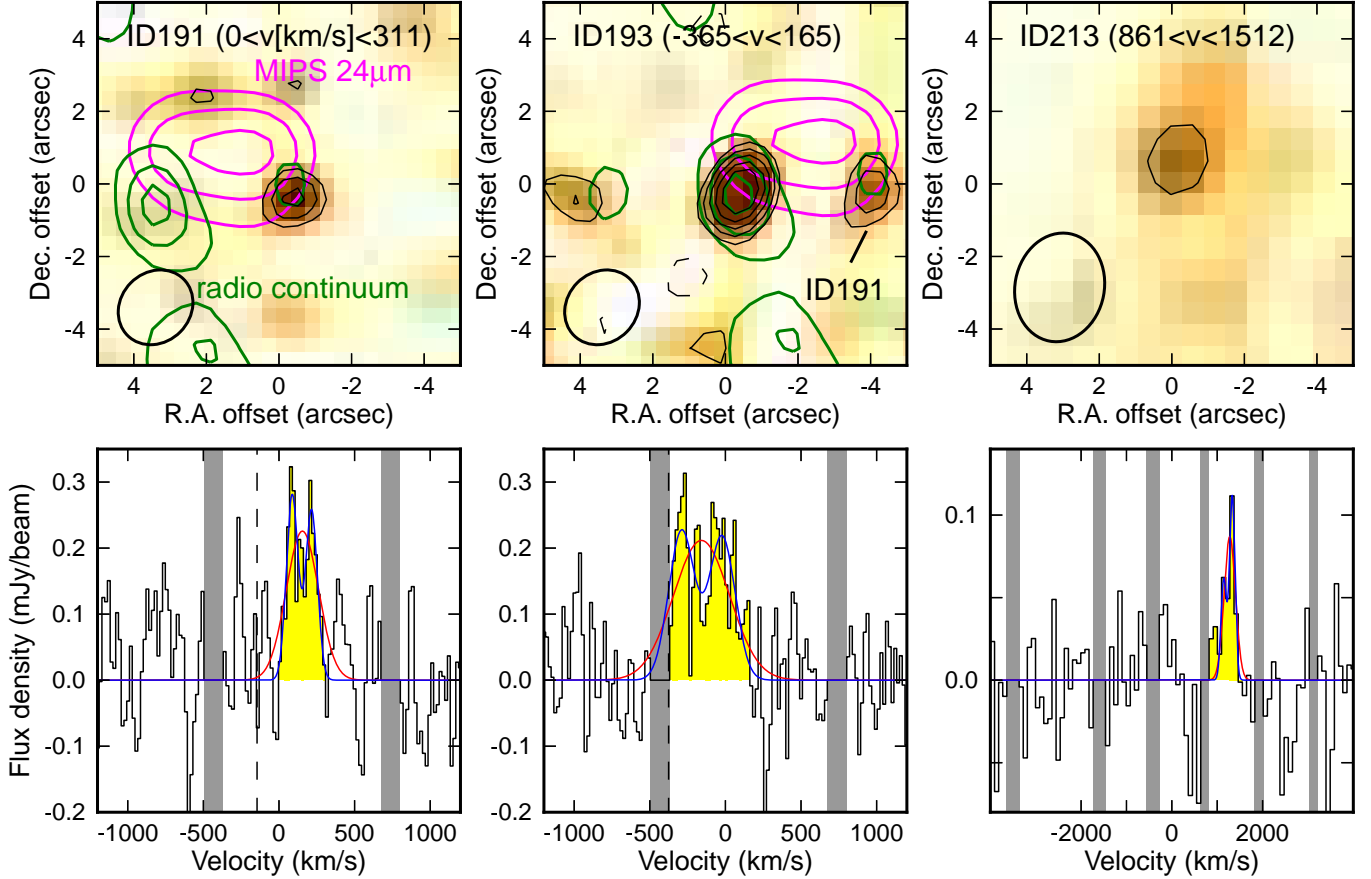


FIG. 2.— (Top) Velocity-averaged maps of the CO emission for three HAEs. The visibility data are averaged over the spectral bins where positive signals are detected (yellow-shaded regions in the bottom panel). The images are obtained using briggs weighting for ID 191/ID 193 and natural weighting for ID 213. The beamsize is at bottom left. Magenta and green contours present MIPS 24  $\mu$ m and radio continuum ( $\nu_{\text{rest}} = 116$  GHz) map, respectively. (Bottom) The CO spectra extracted from the peak position in the top images. The horizontal axis shows the relativistic velocity in the rest frame at  $z = 2.515$ . The velocity resolution is  $18 \text{ km s}^{-1}$ , but the spectrum of ID 213 is binned over the velocity range of  $92 \text{ km s}^{-1}$  to detect a faint emission line. The red and blue lines show the best-fitting profile with single and double gaussian model, respectively. Dashed lines indicate the redshift expected from the  $\text{H}\alpha$  spectroscopy. The channels flagged at the edges of each spectral window are shown by gray-shaded regions.

$J - K_s > 1.38$  and 16 blue HAEs. The two (ID 193 and ID 213) out of four red HAEs are actually detected in the CO emission line while only one (ID 191) out of 16 blue HAEs is detected. Red and massive galaxies tend to be relatively bright in CO emission compared to blue and less massive ones.

Table 1 shows a summary of the properties of CO emission line. We fit their spectra with a single and two-component gaussian model to measure the line width and the velocity-integrated flux,  $S_{\text{CO}} dv$  (Figure 2). The FWHM of CO  $J = 1 - 0$  line profiles is  $250\text{--}450 \text{ km s}^{-1}$ , which is significantly smaller than that of bright SMGs (Ivison et al. 2011, 2012, 2013) and consistent with that of submm faint galaxies like BzK (Aravena et al. 2012). The non-binning spectra with 2 MHz resolution shows a double-peak profile. This irregular feature is closely related to a spatial distribution of molecular gas within galaxies. Local edge-on disks show a double-horn profile but a gap at zero-velocity is widespread in the velocity range and moreover rarely below 50% of the peak flux (e.g. Walter et al. 2008). Such spectra are also seen in color-selected star-forming galaxies at  $z \sim 1.5$  (Daddi et al. 2010) and SMGs at  $z = 1\text{--}3.5$  (Greve et al. 2005). Daddi et al. (2010) demonstrate with numerical

simulations that turbulent and clumpy disks can successfully reproduce the spectra similar to the observed ones but uniform disks cannot. Actually, morphologies of star-forming galaxies become clumpy at  $z > 2$  (e.g. Tadaki et al. 2014). If most of the CO emission is dominated by a few giant clumps, the observed feature can be readily explained. Otherwise, one double profile would reflect a merger between two galaxies with different velocities. Even higher-resolution observations would make it challenging to discriminate between a merger and multiple kpc-scale clumps within a single galaxy. We discuss further the physical process in terms of star-formation mode in Section 4.

### 3.2. Identification of dusty star formation

Although  $\text{H}\alpha$  emission line is one of the best indicators of SFR, it can still miss much of star formation in the case of very dusty galaxies (Koyama et al. 2010). Infrared emission, which is a re-radiation of UV flux of massive stars by their surrounding dust, is very useful for estimating dust-obscured SFRs of galaxies. Three MIPS 24  $\mu$ m sources are identified within the primary beam, and the brightest one with  $S_{24\mu\text{m}} = 425 \mu\text{Jy}$  is located between ID 191 and ID 193 (Figure 2). Since

TABLE 1  
PROPERTIES OF THE H $\alpha$  EMITTERS WITH CO(1-0) LINE DETECTIONS

ID <sup>a</sup>	R.A. (J2000)	Decl. (J2000)	$z_{\text{CO}}$	$v_{\text{CO}}$ FWHM <sup>b</sup> (km s <sup>-1</sup> )	$S_{\text{CO}} dv$ <sup>c</sup> (Jy km s <sup>-1</sup> )	$L'_{\text{CO}}$ (10 <sup>10</sup> K km s <sup>-1</sup> pc <sup>2</sup> )	$L_{\text{IR}}$ (10 <sup>12</sup> L <sub>⊙</sub> )	$M_*$ <sup>d</sup> (10 <sup>10</sup> M <sub>⊙</sub> )
bHAE-191	16 01 11.20	-00 31 19.0	2.5168	251	0.052 ± 0.008	1.5	2.5	5.1
rHAE-193	16 01 11.45	-00 31 19.3	2.5131	437	0.096 ± 0.015	2.8	5.1	4.8
rHAE-213	16 01 11.71	-00 31 11.9	2.5300	294	0.026 ± 0.007	0.8	<1.7	4.6

<sup>a</sup> “bHAE” and “rHAE” indicate blue and red HAEs, respectively, separated at  $J - K_s = 1.38$ .

<sup>b</sup> FWHM of the single gaussian component.

<sup>c</sup> Velocity-integrated flux derived from the two-component model. The errors are calculated on the basis of the signal-noise ratio defined by the 10 MHz binned cube.

<sup>d</sup> Stellar masses are estimated from  $K_s$ -band magnitudes using the relationship between mass-to-luminosity ratios in  $K_s$ -band and  $J - K_s$  colors based on the population synthesis bulge-disk composite models (Kodama et al. 1999).

the PSF size of the MIPS images is too large ( $\sim 6''$ ), we cannot measure the 24  $\mu\text{m}$  flux density of each galaxy.

We use a radio continuum image to deblend the IR emission, because it is a good indicator of extinction-free SFR reflecting the non-thermal emission from supernovae remnants and free-free emission from ionized gas (e.g. Murphy et al. 2011; Thomson et al. 2012). A 33 GHz (116 GHz in the rest frame) image is created with natural weighting by averaging the data over about 2 GHz excluding the frequency range of the CO emission line. The radio data allow us to speculate the relative contribution of each galaxy to the IR emission. We estimate a 116 GHz flux density of  $4.8 \pm 2.6 \mu\text{Jy}$  ( $1.8\sigma$ ) and  $10.2 \pm 2.6 \mu\text{Jy}$  ( $3.9\sigma$ ) for ID 191 and ID 193, respectively (Figure 2). Although ID 191 is marginally detected, it is clear that the blended IR emission is dominated by ID 193. Wuyts et al. (2011) demonstrate with *Herschel*/PACS data that the conversion from observed 24  $\mu\text{m}$  photometries to total IR luminosities,  $L_{\text{IR}}$ , is applicable with  $\sim 0.3$  dex scatter out to  $z = 3$ . Using the luminosity-independent conversion factor (Wuyts et al. 2008), we derive  $L_{\text{IR}} = 2.5 \times 10^{12} L_{\odot}$  and  $L_{\text{IR}} = 5.1 \times 10^{12} L_{\odot}$  for ID 191 and ID 193, respectively. Assuming that the bulk of the total IR luminosity is powered by star formation, we find with the standard calibration of Kennicutt (1998) that ID 193 has a high SFR of  $886 M_{\odot} \text{yr}^{-1}$ . Since the H $\alpha$ -based SFR is  $\sim 40 M_{\odot} \text{yr}^{-1}$ , this object is likely to be strongly attenuated by a large amount of dust ( $A_{\text{H}\alpha} = 3$  mag). On the other hand, ID 213 is not detected at 24  $\mu\text{m}$  and the  $3\sigma$  upper limit of  $L_{\text{IR}} < 1.7 \times 10^{12} L_{\odot}$  is given.

#### 4. DISCUSSION AND SUMMARY

The separation of  $\sim 30$  kpc and the velocity offset of  $\sim 300$  km s<sup>-1</sup> between ID 191 and ID 193 suggest that they are probably in the initial stage of a merger. While ID 193 is already red in the rest-frame optical and bright in the IR/radio emission, ID 191 is blue, meaning less dusty or young stellar populations. Such red-blue pairs are also observed in many SMGs (Ivison et al. 2002). Actually, the derived SFR of  $886 M_{\odot} \text{yr}^{-1}$  in ID193 is higher by a factor of about seven with respect to the  $M_*$ -SFR relation of normal HAEs (*main sequence*; Tadaki et al. 2013) and is similar to that of SMGs, where extremely high star formation is thought to be driven by major mergers (Tacconi et al. 2008; Engel et al. 2010; Ivison et al. 2012). Even the high-redshift disk galaxies fed by cold accretion of gas through cosmic filaments rarely show such extremely high SFRs (Dekel et al. 2009;

Genzel et al. 2008). Although this classification based on colors and SFRs is not straightforward, measurements of  $L_{\text{IR}}/L'_{\text{CO}}$  ratio are helpful for a better understanding of the star-formation mode as it reflects how molecular gas is being turned into stars.

In Figure 3, we plot the two HAEs with CO and IR/radio detections on the  $L_{\text{IR}} - L'_{\text{CO}}$  diagram to compare them with other populations taken from the literature (Matsui et al. 2012; Kuno et al. 2007; Bell & Kennicutt 2001; Aravena et al. 2012; Solomon et al. 1997; Harris et al. 2010; Ivison et al. 2011, 2013; Genzel et al. 2010). Many previous studies at high redshift are based on the CO  $J = 3 - 2$  and  $J = 4 - 3$  line observations, leading to uncertainties in the estimates of the CO  $J = 1 - 0$  luminosities because of variations of gas excitation. Therefore, we use only objects whose CO  $J = 1 - 0$  luminosities have been directly measured. Both red and blue HAE have a higher IR luminosity compared to normal star-forming galaxies at a fixed CO luminosity and are situated close to the regime of low-redshift ULIRGs. On the other hand, some SMGs seem to follow the relation of normal star-forming galaxies. Recent analyses of galaxy morphologies in *Hubble Space Telescope* images show that only 30% of SMGs are associated with ongoing mergers (Wiklund et al. 2014) while most of low-redshift ULIRGs are likely to be merger-driven starbursts (Kartaltepe et al. 2012). This merger fraction of SMGs is highly contentious, with several high-resolution CO studies finding it to be 100% (e.g. Engel et al. 2010). The starburst in ID 191 and ID193 is hard to explain by the first encounter or the final coalescence of a merger between them because the separation of 30 kpc is too large to induce violent star formation (Saitoh et al. 2009). The red HAE with the high SFR, by itself, might be in a late stage of merging where the starburst is induced by a past interaction with another galaxy. In contrast, the IR luminosity measured in the blue one is highly uncertain because of the low signal-noise ratio of  $1.8\sigma$  in the radio emission. Therefore, we do not use ID 191 to characterize the molecular gas properties.

CO  $J = 1 - 0$  observations allow us to derive molecular gas masses independent of its excitation level. The difference of star-formation mode is closely related to a CO to H<sub>2</sub>+He conversion factor,  $\alpha_{\text{CO}}$ . Recent measurements of dust mass and dynamical mass demonstrate that  $\alpha_{\text{CO}} = 3.6 M_{\odot} (\text{K km s}^{-1} \text{ pc}^{-2})^{-1}$  is likely to be appropriate for normal star-forming galaxies at high-redshift (Daddi et al. 2010; Magdis et al. 2011) and



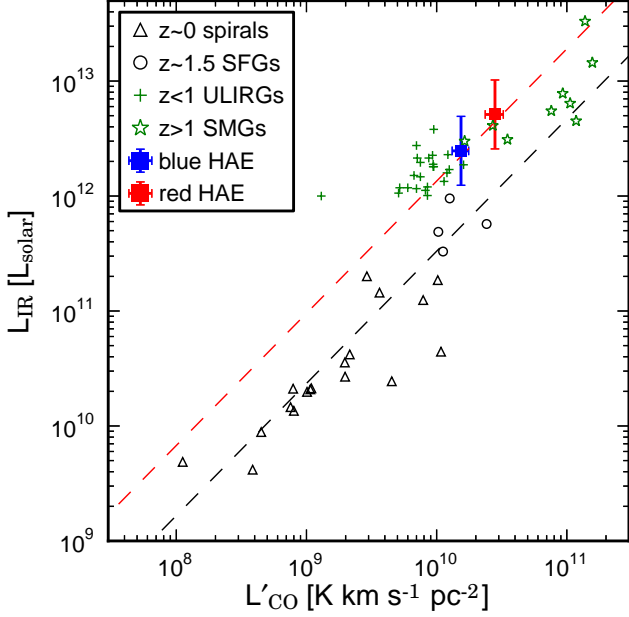


FIG. 3.— IR vs. CO  $J = 1 - 0$  luminosities of the HAEs with CO detection along with SMGs at  $z > 1$  (green stars: Harris et al. 2010; Ivison et al. 2011, 2013), ULIRGs at  $z < 1$  (green crosses: Solomon et al. 1997), optical/near-IR selected star-forming galaxies at  $z > 1$  (black circles: Aravena et al. 2012), and local spirals (black triangles: Matsui et al. 2012; Kuno et al. 2007; Bell & Kennicutt 2001). Dashed black and red lines show the best-fitting relations for normal star-forming galaxies and luminous mergers (Genzel et al. 2010).

$\alpha_{\text{CO}} = 0.8$  is for starburst galaxies (Bolatto et al. 2013; Ivison et al. 2013; Downes & Solomon 1998). Provided that ID193 is in the starburst mode, the molecular gas mass and the gas fraction are  $M_{\text{gas}} = 2.2 \times 10^{10} M_{\odot}$  and  $f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_{*}) \sim 31\%$ , respectively. Its gas depletion timescale is  $\tau_{\text{depl}} = M_{\text{gas}}/\text{SFR} \sim 25$  Myr which is roughly consistent with that of SMGs at similar redshift (Greve et al. 2005; Ivison et al. 2011). Even if using  $\alpha_{\text{CO}} = 3.6$ , we find that  $\tau_{\text{depl}} = 110$  Myr is still shorter compared to normal star-forming galaxies (400 Myr in Salpeter IMF; Tacconi et al. 2013).

In this work, we have discovered a close pair of CO emitting HAEs, ID 191 and ID 193, in the USS1558–003 proto-cluster at  $z = 2.5$ . Because the sum of their stellar masses becomes  $M_{*} \sim 10^{11} M_{\odot}$  and subsequent star-formation activities would further increase it, such

a merger system can be a good candidate of a progenitor of massive quiescent galaxies in local cluster cores. Moreover, ID 193 shows a violent star-formation activity ( $\text{SFR} = 886 M_{\odot} \text{yr}^{-1}$ ), high  $L_{\text{IR}}/L'_{\text{CO}}$  ratio (high SFE) and red optical color. We interpret it as a star-bursting galaxy driven by a gas-rich merger with ID 191 or another galaxy. Given the identification of a rare event with the depletion timescale of  $\tau_{\text{depl}} = 25$  Myr, merger events could frequently occur in the extremely dense environment as surrounding galaxies are expected to be dragged by a gravitational potential of a large halo. By dissipative processes between gas-rich galaxies, the systems that have undergone merger events could be observed as the remnants with little or no rotation (slow rotators) at  $z = 0$  (Naab et al. 2013). This hypothesis can naturally account for the observational results that slow rotators are frequently observed in local cluster cores (Cappellari et al. 2011). To confirm whether gas-rich merger events are in fact common in high-density environments at  $z > 2$ , we need a statistical sample. The combination of a wide-field H $\alpha$  narrow-band imaging with a future wide-field observation of CO  $J = 1 - 0$  emission with ALMA Band-1 ( $> 7$  arcmin $^2$ ) will be powerful for such studies of star-formation modes in proto-clusters at high redshift.

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## REFERENCES

- Aravena, M., Carilli, C. L., Salvato, M., et al. 2012, MNRAS, 426, 258  
 Bell, E. F., & Kennicutt, Jr., R. C. 2001, ApJ, 548, 681, 681  
 Bolatto, A. D., Wolfire, M., & Leroy, A. K. 2013, ARA&A, 51, 207  
 Cappellari, M., Emsellem, E., Krajnović, D., et al. 2011, MNRAS, 416, 1680  
 Daddi, E., Bournaud, F., Walter, F., et al. 2010, ApJ, 713, 686  
 Dekel, A., Birnboim, Y., Engel, G., et al. 2009, Nature, 457, 451  
 Downes, D., & Solomon, P. M. 1998, ApJ, 507, 615  
 Dressler, A., Oemler, Jr., A., Couch, W. J., et al. 1997, ApJ, 490, 577  
 Emsellem, E., Cappellari, M., Krajnović, D., et al. 2011, MNRAS, 414, 888  
 Engel, H., Tacconi, L. J., Davies, R. I., et al. 2010, ApJ, 724, 233  
 Frayer, D. T., Ivison, R. J., Scoville, N. Z., et al. 1998, ApJ, 506, L7  
 Geach, J. E., Smail, I., Moran, S. M., et al. 2011, ApJ, 730, L19  
 Genzel, R., Burkert, A., Bouché, N., et al. 2008, ApJ, 687, 59  
 Genzel, R., Tacconi, L. J., Gracia-Carpio, J., et al. 2010, MNRAS, 407, 2091  
 Greve, T. R., Bertoldi, F., Smail, I., et al. 2005, MNRAS, 359, 1165  
 Harris, A. I., Baker, A. J., Zonak, S. G., et al. 2010, ApJ, 723, 1139  
 Hayashi, M., Kodama, T., Tadaki, K.-i., Koyama, Y., & Tanaka, I. 2012, ApJ, 757, 15  
 Ivison, R. J., Papadopoulos, P. P., Smail, I., et al. 2011, MNRAS, 412, 1913  
 Ivison, R. J., Greve, T. R., Smail, I., et al. 2002, MNRAS, 337, 1  
 Ivison, R. J., Smail, I., Amblard, A., et al. 2012, MNRAS, 425, 1320  
 Ivison, R. J., Swinbank, A. M., Smail, I., et al. 2013, ApJ, 772, 137

- Kartaltepe, J. S., Dickinson, M., Alexander, D. M., et al. 2012, *ApJ*, 757, 23
- Kennicutt, Jr., R. C. 1998, *ARA&A*, 36, 189
- Kodama, T., Bell, E. F., & Bower, R. G. 1999, *MNRAS*, 302, 152
- Kodama, T., Hayashi, M., Koyama, Y., et al. 2013, in *IAU Symposium*, Vol. 295, *IAU Symposium*, ed. D. Thomas, A. Pasquali, & I. Ferreras, 74–77
- Kodama, T., Tanaka, I., Kajisawa, M., et al. 2007, *MNRAS*, 377, 1717
- Koyama, Y., Kodama, T., Shimasaku, K., et al. 2010, *MNRAS*, 403, 1611
- Kuno, N., Sato, N., Nakanishi, H., et al. 2007, *PASJ*, 59, 117
- Magdis, G. E., Daddi, E., Elbaz, D., et al. 2011, *ApJ*, 740, L15
- Makovoz, D., & Khan, I. 2005, in *Astronomical Society of the Pacific Conference Series*, Vol. 347, *Astronomical Data Analysis Software and Systems XIV*, ed. P. Shopbell, M. Britton, & R. Ebert, 81
- Matsui, K., Sorai, K., Watanabe, Y., & Kuno, N. 2012, *PASJ*, 64, 55
- McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in *Astronomical Society of the Pacific Conference Series*, Vol. 376, *Astronomical Data Analysis Software and Systems XVI*, ed. R. A. Shaw, F. Hill, & D. J. Bell, 127
- Mihos, J. C., & Hernquist, L. 1996, *ApJ*, 464, 641
- Murphy, E. J., Condon, J. J., Schinnerer, E., et al. 2011, *ApJ*, 737, 67
- Naab, T., Oser, L., Emsellem, E., et al. 2013, *ArXiv e-prints*, arXiv:1311.0284
- Neri, R., Genzel, R., Ivison, R. J., et al. 2003, *ApJ*, 597, L113
- Saitoh, T. R., Daisaka, H., Kokubo, E., et al. 2009, *PASJ*, 61, 481
- Salpeter, E. E. 1955, *ApJ*, 121, 161
- Shimakawa, R., Kodama, T., Tadaki, K.-i., et al. 2014, *MNRAS*, 441, L1
- Solomon, P. M., Downes, D., Radford, S. J. E., & Barrett, J. W. 1997, *ApJ*, 478, 144
- Tacconi, L. J., Genzel, R., Smail, I., et al. 2008, *ApJ*, 680, 246
- Tacconi, L. J., Neri, R., Genzel, R., et al. 2013, *ApJ*, 768, 74
- Tadaki, K.-i., Kodama, T., Tanaka, I., et al. 2013, *ApJ*, 778, 114
- . 2014, *ApJ*, 780, 77
- Tanaka, I., Breuck, C. D., Kurk, J. D., et al. 2011, *PASJ*, 63, 415
- Thomson, A. P., Ivison, R. J., Smail, I., et al. 2012, *MNRAS*, 425, 2203
- Walter, F., Brinks, E., de Blok, W. J. G., et al. 2008, *AJ*, 136, 2563
- Wiklund, T., Conselice, C. J., Dahlen, T., et al. 2014, *ApJ*, 785, 111
- Wuyts, S., Labbé, I., Schreiber, N. M. F., et al. 2008, *ApJ*, 682, 985
- Wuyts, S., Förster Schreiber, N. M., Lutz, D., et al. 2011, *ApJ*, 738, 106